

Space Qualification of Photonic Devices

Quiesup Kim^{*a}, Chris J. Wrigley^{**a}, Thomas J. Cunningham^a, and Bedabrata Pain^a

^aJet Propulsion Laboratory, California Institute of Technology
Pasadena, California 91109-8099

ABSTRACT

Key optical elements for space qualification plans of photonic devices are overviewed. Device parameters and qualifying procedures were discussed to assure the reliability of newly developed photonic devices needed for potential usage in space environments. The goal is to gradually establish enough data to develop a space qualification guideline for devices using empirical and numerical models to assess reliability including the lifetime degradation of devices for long-term space applications. Optical, electrical and mechanical device requirements of newly integrated photonic devices (diode lasers and detector arrays) were presented. Monolithically integrated active pixel InGaAs detector arrays were compared, as examples, with those hybridized with CMOS silicon multiplexers in terms of their performances and reliability. Adapting the existing fiber optical (1.55 μm) communication technology, this integration will be an ideal optoelectronic system for dual band (0.5-2.5 μm , Visible/IR) applications near room temperature for use in geological material research and in atmospheric gas sensing in space. For target identification on earth, however, there are concerns about the effectiveness of the device quality, reliability, and prevention of device failure in preparation for multifunctional, transportable shipboard surveillance, night vision, and emission spectroscopy in air and on Mars terrestrial applications.

Keywords: Space Qualification, Reliability, Low power, InGaAs PIN Array, InP JFETs Array.

1. INTRODUCTION

A general guideline for qualification of photonic devices (PDs) for space applications is needed but is not available. The rationale for not publishing a strict qualification standard is the fact that the PD industry is rapidly evolving, and, therefore, it would not be prudent to set limits on that evolution. In addition, it is not possible to guess the needs of every system being planned or the reliability requirements of every system. For example, PD users may request a relaxation of the recommended qualification methodology to lower the part cost if a space mission has a short expected lifetime or if the total satellite cost is small. Alternatively, very expensive satellites with a long projected lifetime will normally be qualified to a higher standard than even that recommended in this qualification guide. The important point is that whenever reliability qualification standards are relaxed, either through the deletion of some tests, or screens, or by a reduction in the number of parts tested, up-front PD costs are lowered at the price of increased risk of system failure. This talk addresses the general guidelines.

Prior to qualifying parts for hardware of a specific mission, the mission should be well defined including its objectives, environments, duration, and any specific conditions or unknown variables as shown in **Figure 1**.

A mission-critical failure is defined to be a failure that results in the permanent loss of data from more than one scientific instrument during the mapping phase, loss of the relay capability during the relay phase, the failure to achieve and maintain the proper orbit or pointing control to within specified tolerances, the loss of science-critical engineering telemetry required for attitude determination, or the failure to achieve the quarantine orbit (if required) prior to the end of the mission. Any PDs for specified scientific instruments should be qualified by this general guideline for the success of the mission.

^{*a}Quiesup.Kim@jpl.nasa.gov; Phone: (818) 354-6080; Fax: (818) 393-0045, <http://www.jpl.nasa.gov>; Jet Propulsion Laboratory, 4800 Oak Grove Dr., Pasadena, California 91109-8099; ^{**a}chris.j.wrigley@jpl.nasa.gov; Phone: (818) 354-3365; Fax: (818) 393-0045, <http://www.jpl.nasa.gov>; Jet Propulsion Laboratory, 4800 Oak Grove Dr., Pasadena, California 91109-8099

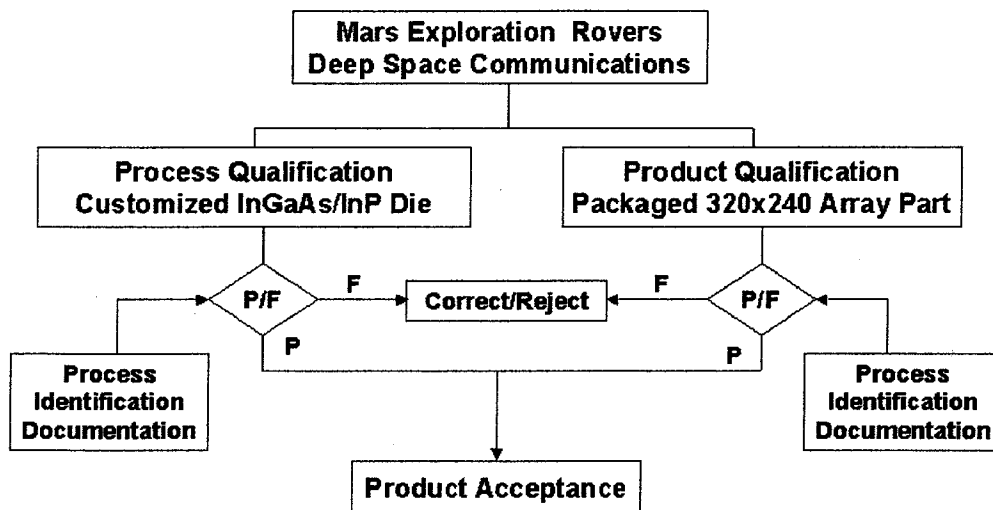


Figure 1. Recommended Qualification Methodology.

2. QUALIFICATION METHODOLOGY

Qualified Manufacturers Listing (QML) programs¹ with screening procedures use more traditional qualification methodologies. The steps are (1) Company Certification, (2) Process Qualification (**Figure 2**), (3) Product Qualification (**Figure 3**), and (4) Product Acceptance. Company Certification outlines the procedures and management controls the manufacturer should have in place to assure the quality of its optoelectronic and photonic devices. Process Qualification outlines a procedure the manufacturer should follow to assure the quality, uniformity, and reproducibility of PDs from a specific fabrication process. Product Qualification encompasses a set of simulations and measurements to establish the optical, electrical, thermal, and mechanical reliability characteristics of a particular optoelectronic device design. Lastly, Product Acceptance is a series of tests or screens performed on the deliverable that is normally practiced by PD manufacturers and their customers to satisfy high reliability space program requirements and provide a specific reliability and qualification information pertinent to that particular PD product and a specific space mission environment.

A recommended procedure for acceptance of a few specific optoelectronic device, for example, for previous space missions is outlined in section 3. Although the methodologies recommended here appear rigid and specific, they should not be viewed as such. In fact, the qualification methodology not only permits but rather requires both the manufacturer and the mission manager to determine many of the details. Instead of presenting specifications for reliability, this talk presents the questions a photonic device user should ask of the manufacturer to assure a reasonable level of reliability, and at the same time it tries to present to the device manufacturer the methodologies that have been accepted and practiced by some members of the industry in the hope that a standard qualification procedure may develop. Furthermore, it should be used with the other qualification methods. The details of this qualification methodology depend on the type of a specific missions and device being fabricated, and the devices incorporated into the subsystem, along with the reliability concerns and failure mechanisms, the testability of the circuit and the effect of the package has on the PD reliability.

A general guideline practice for the space qualification of specific photonic devices is developed and shown based on a process qualification methodology, exemplifying specific devices as shown in **Figure 2**.

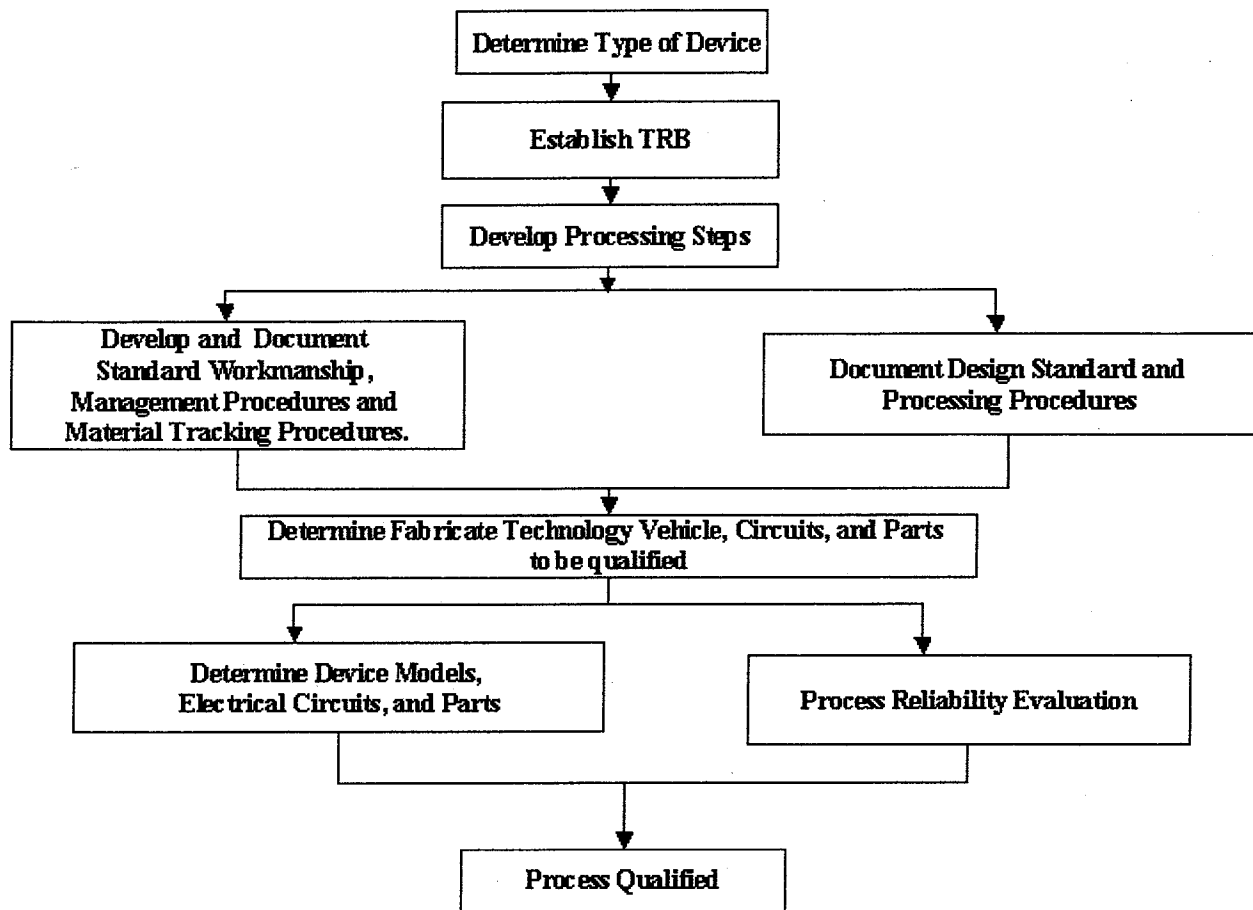


Figure 2. Recommended process qualification.

3. SPACE QUALIFICATIONS

This general guideline covers the provisional plan for photonic devices intended for use in space missions and critical ground-support equipment applications. The part number shall consist of the number of this specification followed by the detail specification slash number and applicable dash numbers. The photonic devices shall be the parts used in space missions, such as laser diodes (single/multiple modes), PIN receiver diodes and transistors, fibers (single/multiple mode), index guided: p-InP/n-InGaAs/p-InP, opto-couplers, optical amplifiers, and optical switches.

The major critical variable to qualify the photonic devices is the lifetime defined by the performance of the devices under a specific space environment, such as operating temperatures, bias current/voltage, output power, spectral width, and data rates. For example, the lifetime of a laser diode is decreased by half for every 10°C increase of the operating temperatures ($\tau = \exp(-E_a/kT)$ where E_a , k , and T are the activation energy, the Boltzman constant, and the operating temperature, respectively). The primary function of the space qualification of the optoelectronic devices, specifically in deep-space optical communications, is to provide reliable devices for successful completion of the mission. This plan then becomes a major document to screen the parts with proper traveler of the device.

The plan should include at least purpose and requirements of management and parts depending upon a specific device. This section defines specific requirements of optoelectronic parts program recommendations and their applicability to NASA missions.

The specific space mission Parts Program Engineer (PPE) shall be responsible for the overall implementation and enforcement of this portion of the Mission Assurance Plan. Only parts of acceptable quality, reliability, and radiation characterization compliance, as demonstrated through evaluation and/or verified performance, shall be selected for application in flight equipment. Use of lower quality level parts shall not be allowed without an approved waiver.

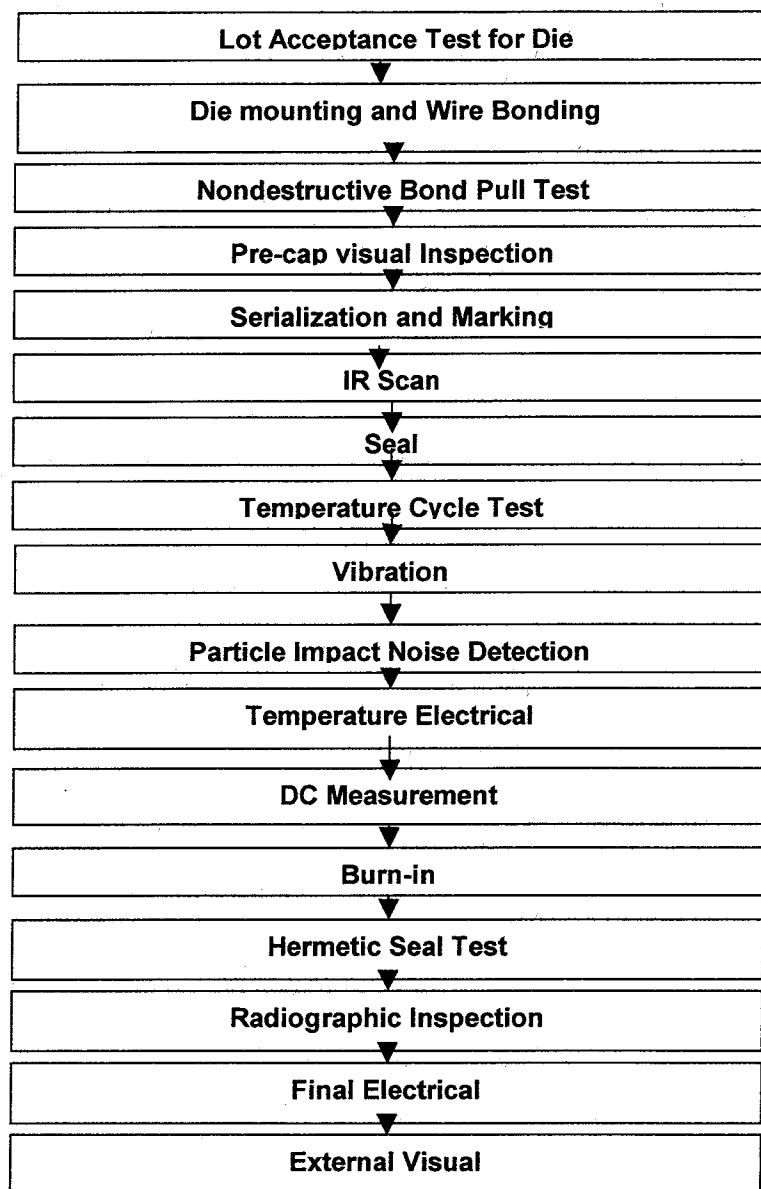


Figure 3. Recommended Product Qualification.

When, based on technology maturity, development cost and risk, the project decides to implement a Known Good Die program for hybrid microcircuits and multi-chip modules, a Known Good Die (KGD) program. Whenever either a standard or nonstandard part fails to fully comply with the standard or nonstandard parts requirements identified herein, and it is decided that the parts will be used in a flight system, a waiver shall be initiated and submitted to the Mission Assurance Manager for approval.

Digital logic circuitry (including the microprocessor, microcontroller and all custom designs) for optoelectronic devices shall be tested. Quiescent current tests shall be based on a set of vectors that will toggle the nodes. Additional tests shall be conducted that include: 1) operating speed (or maximum testable speed) functional test to verify all functions of the design and 2). DC and AC parametric test vectors. For mixed-signal digital portions shall be tested separately from the analog portions; the digital parts will be tested as above. The analog portions shall be SPICE modeled and tests performed to measure the correspondence of the actual die to the SPICE models. The designer and the die manufacturer will jointly specify these tests. Each die must meet its analog performance specifications. As a minimum, these tests shall be performed. Parametric tests shall be performed over the full operating temperature range of selected missions.³

A minimum sample of available die from each control wafer run shall be packaged, tested and subjected to life test. Read and record variables test data shall be taken at each test stage of the Life tests; it is anticipated that this data will be used to verify the Worst Case Analysis (WCA) and to characterize the parameter variations. This characterization will be used to evaluate the failure model vs. test data.

All parts shall be selected to meet the highest radiation levels available as indicated in the following paragraphs. All selected parts shall meet the design and manufacturing requirements as specified in a specific space mission Environmental Design and Test Requirements.

All Parts shall be selected to meet the highest total ionizing dose (TID) levels available. All parts shall be selected to meet a minimum TID level of 100k (Si) at the die level. Parts not meeting this requirement shall not be used without an approved waiver. The external radiation environment is specified in the specific space mission Project Environmental Requirements.

All parts shall be evaluated and reported to JPL for displacement damage sensitivity to assure that parametric degradation due to displacement damage has been accounted for in the subsystem worst-case analysis. Selected parts shall have a minimum susceptibility to displacement damage of 10^{13} n/cm² equivalent 1 MeV neutron fluence. Potentially susceptible parts include but are not limited to optical devices, photodetectors, charge, coupled devices, optocouplers, light emitting diodes, laser diodes bipolar power transistors and precision bipolar linear devices. Displacement damage (beyond that associated with total dose) may also be an issue with neutrons and heavy ions in optoelectronics and certain linear devices.

All CMOS devices (including those with epitaxial layers) shall be subject to latchup evaluation. All parts shall exhibit no latchup with a linear energy transfer (LET) of 75 MeV-cm²/mg, for example, for Mars missions.

All microcircuits containing bistable elements (e.g. flip-flops, counters, RAMs, microprocessors, etc.) shall be characterized so that an upset rate or upset probability calculation can be performed. A sufficient number of data points (a minimum of three) shall be taken to determine the curve of device cross-section versus LET (to saturation or to an LET).

All power transistors operated in the off-mode may be susceptible to and shall be evaluated for single event burnout (SEB) at the lowest application V_{BE} or V_{GS} . The survival voltage (V_{CE} for bipolar and V_{DS} for MOSFETs) shall be established. All power MOSFETs operated in the off-mode may be susceptible to, and shall be evaluated for single event gate rupture (SEGR) at the lowest application V_{GS} . The established survival voltage (V_{DS}) shall be established Residual inventory (i.e., heritage parts) refers to parts previously approved and procured for prior flight Project applications. Residual electronic parts may be used for a specific space mission only if they meet all. All parts shall be traceable by manufacturer's part number, serial number, and lot date code

Destructive physical analyses shall be performed on a sample of each manufacturing lot-date code for microcircuits, oscillators, resistor networks, crystals, filters, ceramic capacitors, relays, inductors, and all nonstandard packaged parts. MIL-C-39010 inductors/transformers shall be sectioned to examine the adequacy of the termination. The results of the DPA shall be evaluated by the procuring activity and the lot shall be accepted or rejected based on the criteria of the specification.

Electrostatic discharge damage or degradation may occur in static-sensitive electronic parts during handling of the parts from procurement through incoming inspection, testing, screening, storing and final assembly/test. To protect static-sensitive parts from ESD, handling of parts shall be controlled by the requirements.

All hardware-delivering design agencies shall establish and implement a system to review Government Industry Data Exchange Program (GIDEP) Alerts, take appropriate action, and notify their respective GIDEP Alert coordinators of significant parts problems that may warrant issuance of new Alerts. Design agencies which do not presently receive Alerts directly should request distribution from the proper offices. The design agency is responsible for reviewing all Alerts, and for immediately reporting corrective action for applicable Alerts (i.e. for parts used in the hardware) to the project. The design agency shall present a report at the Critical Design Review (CDR), and another at the Pre-Ship Review, that lists all of the Alerts which are pertinent to the parts used in the flight design, the possible impact should the part fail, and the actions proposed and those taken. It is the responsibility of the design agency to avoid the use of defective parts in flight equipment.

Failure analysis is required for all part failures that occur subsequent to screening. The only exceptions are parts damaged by human error (e.g., improper installation). Analysis shall be carried to the point that lot dependency of the failure mode can be determined. Failure analysis reports shall be written to document the analysis approach, the determined failure mode and mechanism (i.e., cause) responsible for the failure, and the corrective actions required to prevent recurrence of the failure.

4. DISCUSSIONS

A manufacturer who has standardized production around a single technology will often qualify the entire production line. In doing so, the manufacturer attempts to demonstrate that the entire process of designing and fabricating photonic devices using the stated technology is under its control. In addition, the manufacturer establishes an optoelectrical performance and reliability baseline for all components fabricated using the process. This has advantages for both the manufacturer and the user of the photonic device. For the manufacturer, it saves costs and time on the fabrication of future photonic devices, since the reliability and functional performance of the components constituting the photonic device have already been established. For the photonic device user, there is a certain level of comfort in buying parts from a production line with a history of supplying reliable photonic devices, in addition to the reduced qualification time and therefore delivery time that should be possible.

Process qualification is a set of procedures a manufacturer follows to demonstrate that they have control of the entire process of designing and fabricating a photonic device using a specific process (e.g., Laser diode, PIN Detectors, JFET, HEMT). It addresses all aspects of the process including the acceptance of starting materials, documentation of procedures, implementation of handling procedures, and the establishment of lifetime and failure data for devices fabricated using the process. Since the goal of process qualification is to provide assurance that a particular process is under control and known to produce reliable parts, it needs to be performed only once, although routine monitoring of the production line is standard. It is critical to remember that only the process and basic circuit components are being qualified. No reliability information is obtained for a particular PD design.

Although process qualification is intended to qualify a defined fabrication procedure and device family, it must be recognized that the technology, for example InGaAs/InP [1], is constantly evolving, and this technology evolution requires the continual change of fabrication procedures. Furthermore, minor changes in the fabrication process to account for environmental variations, incoming material variations, continuous process improvement, or minor design modifications may be required. All of these changes in the process are permitted and frequently occur under the direction of the technology review board (TRB). Thus, strict application of the commonly used phrase, "freezing the production process" does not apply.

The internal documents and procedures used by most manufacturers for process qualification are summarized in Figure 2. In addition, the QML program [2] provides guidelines for process qualification. The first step in the procedure is for the manufacturer to determine the family of devices to be fabricated and the technology that will be

used in the fabrication-for example, a 0.5 μm , Zn-diffused JFET technology with Si_3N_4 capacitors and various ohmic contacts. Second, the manufacturer will establish a TRB to control the process qualification procedure. After all of the processing steps have been defined and documented, the workmanship, management procedures, material tracking procedures, and design procedures should be documented.

The qualification process also involves a series of tests designed to characterize the technology being qualified. This includes the electrical as well as the reliability characteristics of components fabricated on the line. Some of these tests are performed at wafer level and include the characterization of parametric monitors, Technology Characterization Vehicles (TCVs), and standard examining circuits. Other tests require the mounting of circuits or elements onto carriers. All of these tests and the applicable procedures are an integral part of the qualification program and provide valuable reliability and performance data at various stages of the manufacturing process. The number of circuits or devices subjected to each test will normally be determined by the TRB and the rationale for their decision will become part of the process qualification documentation. In general, a higher level of confidence in the reliability data exists if more circuits are tested, but this is offset by the fact that after a certain level of testing, the incremental gain in confidence is minor compared to the cost of testing. Since the stability of the process is being determined as part of the process qualification, the manufacturer will typically fabricate and test components from several wafer lots. A series of tests that is recommended to characterize the electrical and thermal limitations of the devices or circuits should be provided. The performance limitations obtained from these tests often become the basis for limits incorporated into the design and layout rules.

Note that the process-qualification procedure is QML-like and therefore addresses topics similar to those of the company certification. The major difference is that company certification is performed by the customer, whereas process qualification is self-imposed by the manufacturer, often before customers are identified.

5. SUMMARY

A few important aspects of optoelectronic device qualification were discussed. First, although the manufacturer is ultimately responsible for delivering a reliable device, the reliability of the end item deliverable system rests with the system user. Therefore, it is within both party's interests to understand the expected both optical and electrical performance requirements and operating environment of not just the device, but also the system itself. While this helps the manufacturer select the best technology for the device and deliver a more reliable part, it requires the device user to share information with the manufacturer. Furthermore, although the organization of the qualification methodology is representative of what device manufacturers and users currently use, the content of the qualification process is the essential ingredient. The photonic device user should not discount a manufacturer's proposal because the manufacturer does not organize its procedures in the same way or use the same terms and phrases described here.

Key elements of space qualification of optoelectronic devices optical were presented. Efforts were concentrated for the reliability concerns of the optoelectronic devices needed for potential applications in a specific space environments to develop a qualification plan of newly developed photonic parts. This working model may fit to a device that is newly developing for a venture business.

ACKNOWLEDGMENTS

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- [3]. Richard Kemski, "Outer Planets/Solar Probe Project Mission Assurance Plan", JPL Internal document D-18353, 2000.

The Occurance of “Nan(n)o” in the Georef Database

- Over 300 keywords containing “Nanno” or “Nano”

Keyword	Results
Nannofossil	5,660
Nannoplankton	1,206
Nannobacteria	19
Nannophase	18
Nanocomposites	18
Nanocrystalline	13
NanoSIMS	2
Nanopetrographic	1

Keyword	Results
Microfossil	104,631
Micropaleontology	6,036
SEM	14,093
TEM	4,816
Geomicrobiology	788
SIMS	369
HRTEM	164
EELS	25





Web Search for “Nan(n)o”

➤ Google Search

- ✧ Nano + geology = 3320 results.
- ✧ Nanno + geology = 5600 results.

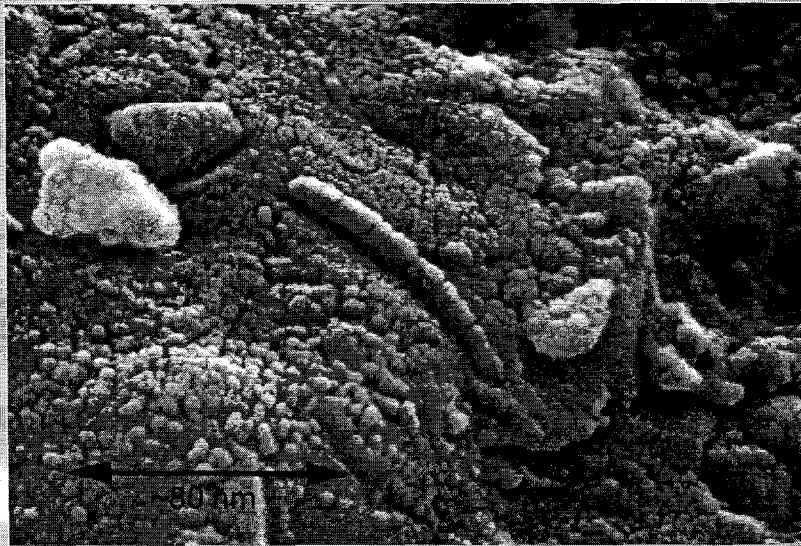
➤ Results included:

- ✧ Nannofossil Laboratory at Scripps Institute of Oceanography, University of California - San Diego.
- ✧ North American Micropaleontology Section, Society for Sedimentary Geology.
- ✧ United States Geological Service
- ✧ www.nannos.com
- ✧ British Micropaleontological Society
- ✧ International Union of Geological Sciences

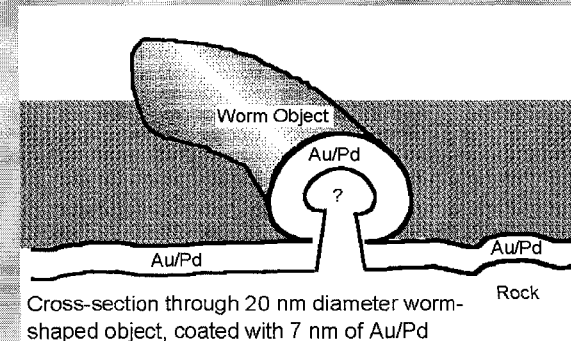


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How do you characterize “Nannofossils?”

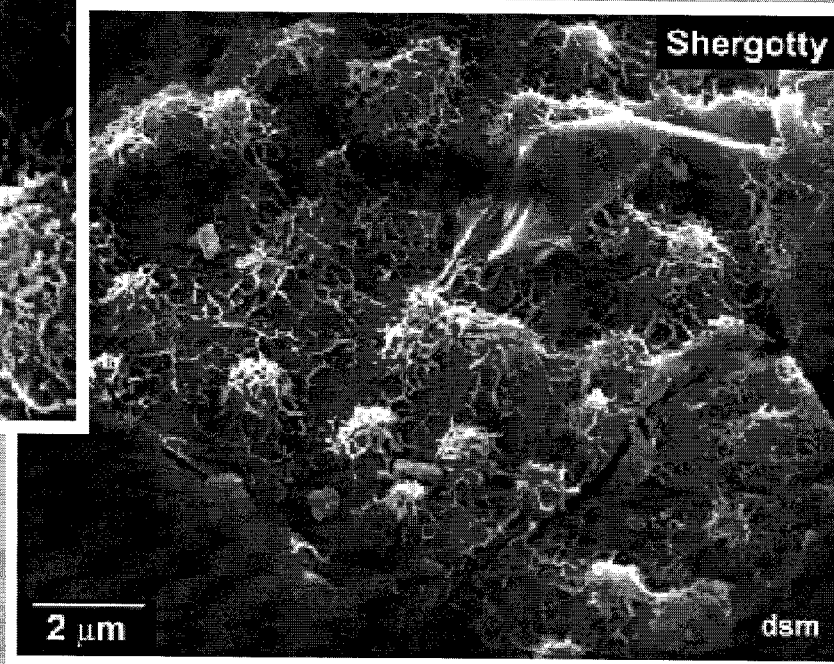
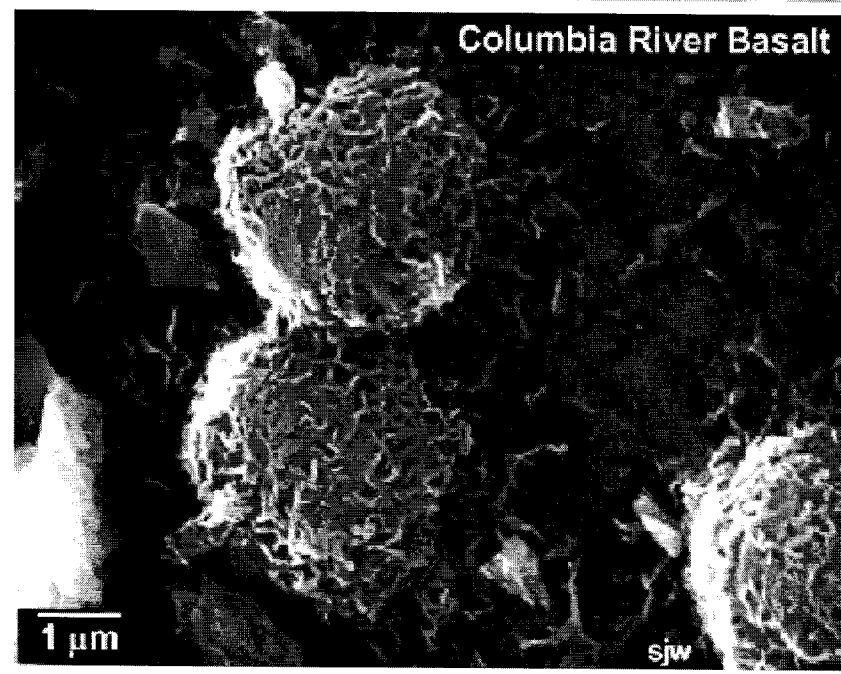


An SEM micrograph of the "fossil nanobacteria" found in ALH84001 by McKay, et al. [1996].



A schematic diagram of a possible cause of the "fossil nanobacteria" found in ALH84001 by McKay, et al. (1996) as discussed by Steele, et al. (1998) and Bradley, et al. (1997).

Microfossils 1

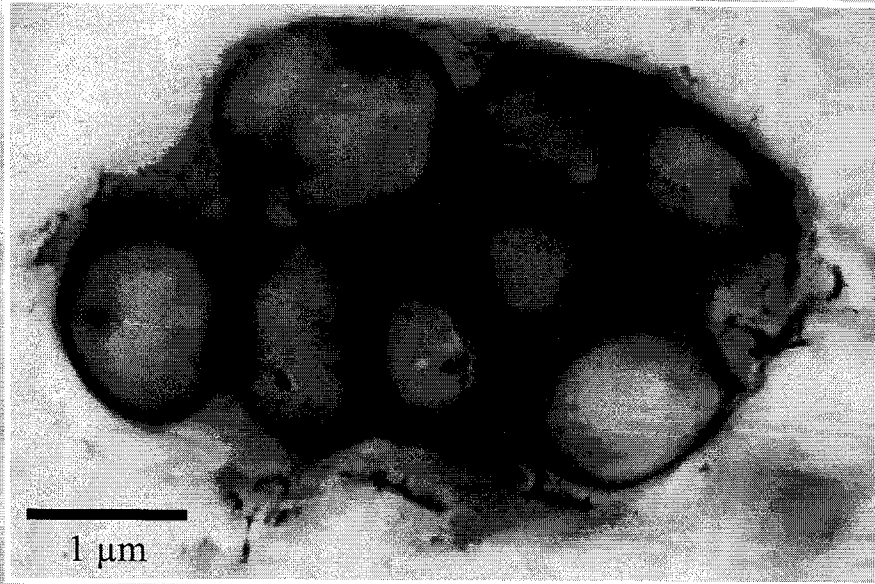


From Gibson, et al. (2001) Precambrian Research.

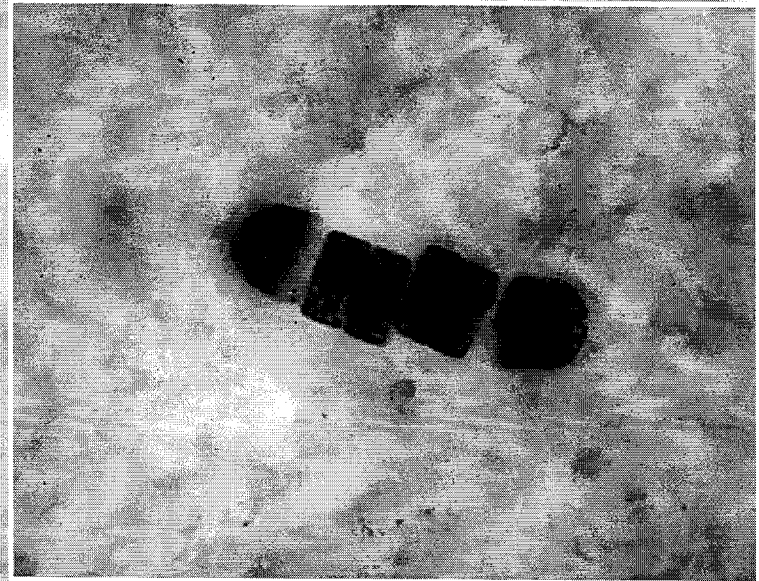


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Fossil Cyanobacteria



Colonial chroococcalean form, probably
Myxococcoides minor



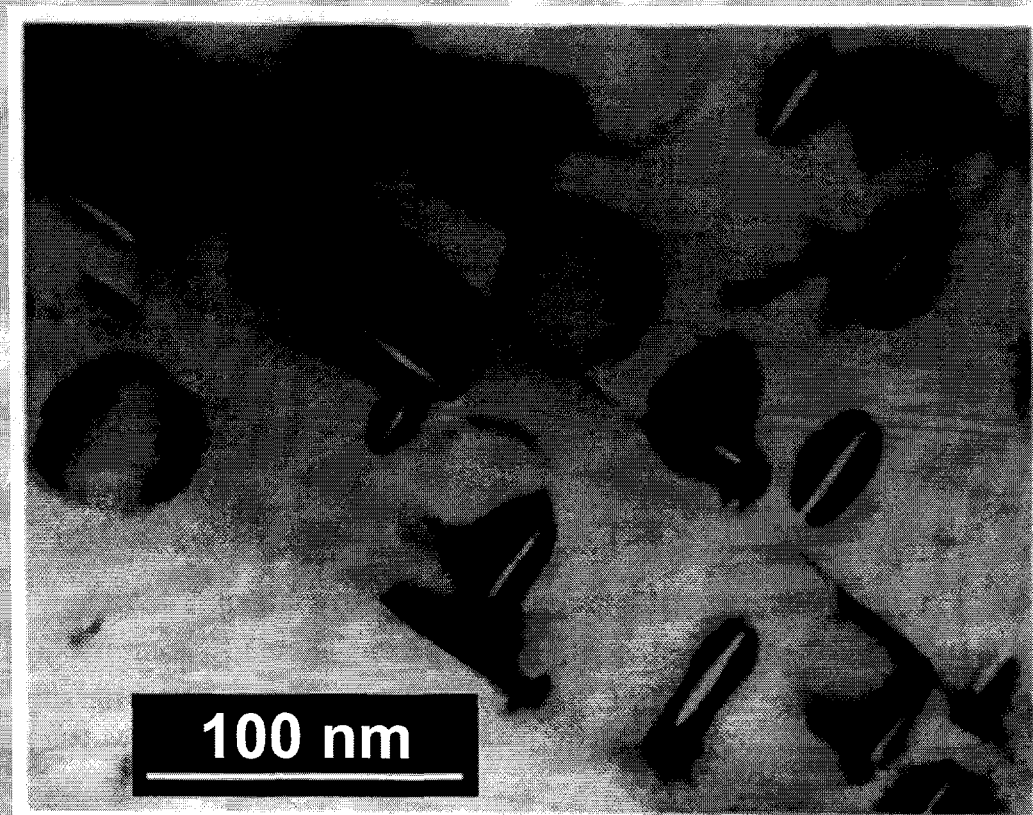
Filamentous *Palaeolyngbya*

From Museum of Paleontology, University of California, Berkeley (2001) Precambrian Research
<http://www.ucmp.berkeley.edu/bacteria/cyanofr.html>



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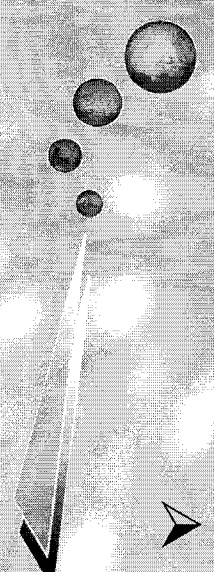
Metamorphic Geology



From Sitzman, et al. (2000) American Mineralogist.



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Techniques for Morphological, Elemental and Chemical Analysis of Sub-Micron Features

➤ Widely used methods:

- ✧ Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy.
- ✧ Electron Probe Microanalysis (EPMA) and Wavelength Dispersive Spectroscopy (WDS).
- ✧ Transmission Electron Microscopy (TEM) and Electron Energy Loss Spectroscopy (EELS).

➤ “New” methods:

- ✧ Local Electrode Atom Probe (LEAP) / Atom Probe Tomography (APT).
- ✧ Focused Ion Beam Secondary Ion Mass Spectrometry (FIB-SIMS).



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Objectives of this work

- A 3D near-atomic scale elemental map of a geological sample.
- Demonstrate the planetary science potential of the Local Electrode Atom Probe (LEAP).
 - ✧ Potential of LEAP analysis for non-conductive samples:
 - ✧ Terrestrial geology and geomicrobiology,
 - ✧ Apollo samples from the Moon,
 - ✧ Samples returned by the Stardust, Genesis and Mars missions.
 - ✧ Mars Sample Return.
- Demonstrate the potential of the Mini-LEAP for the *in-situ* analysis of planetary materials.
 - ✧ NASA is currently developing a prototype Mini-LEAP at JPL.
- Determine the composition of the spinel lamellae in LP204-1 for purposes of interpreting the thermal history.




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Why Magnetite?

- A common mineral on Earth and Mars.
- One of the more conductive minerals.
 - ✧ Resistivity = 52×10^{-4} ohm-cm.
- This particular magnetite contains disk-shaped exsolutions approx. 40 nm in diameter, 1-3 nm thick and about 10^4 platelets/ μm^3 .
- EDS shows Mn and Al concentrated in these precipitates.
- Quantitative analysis has been limited by the thickness of this second phase.



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Focused Ion Beam Secondary Ion Mass Spectrometry (FIB-SIMS)

- Makes use of highly focused Gallium liquid metal ion source (LMIS) to sputter and ionize atoms in the sample. Spatial resolution \sim spot size \sim 50 nm.
- Secondary ions are collected and measured using a quadrupole mass spectrometer.
- Ion beam is capable of milling and flattening the surface to expose interior and remove differential sputtering effects.



<http://www.cea.com/cai/simstheo/ionspu.htm>



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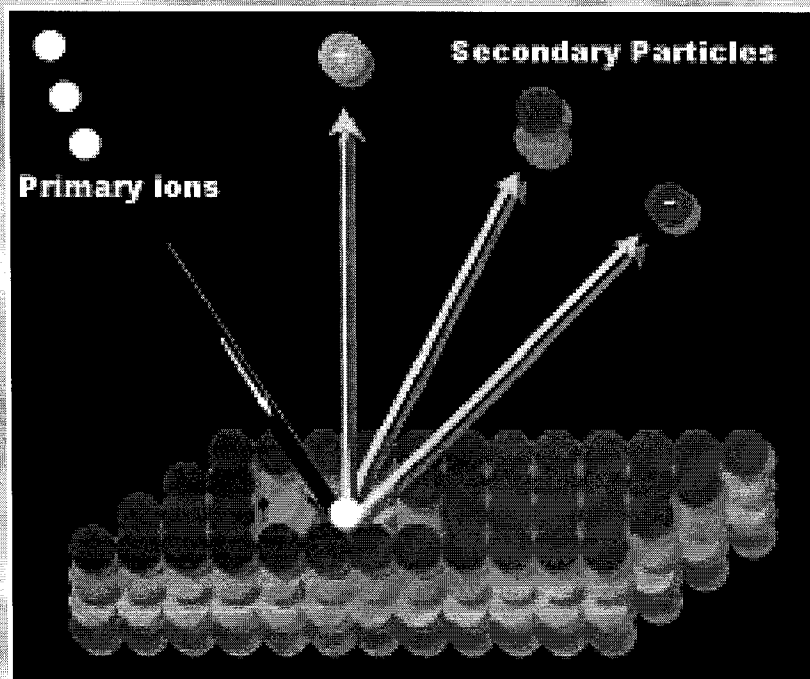
Related State-of-the-Art Instruments

- FIB-SIMS (FEI) University of Virginia
- TOF-SIMS (ION-TOF) with FIB attachment, Smithsonian Institution
- NanoSIMS™ (Cameca)
 - ✧ Washington University, St. Louis
 - ✧ Max-Planck-Institute for Chemistry
 - ✧ Curie Institute

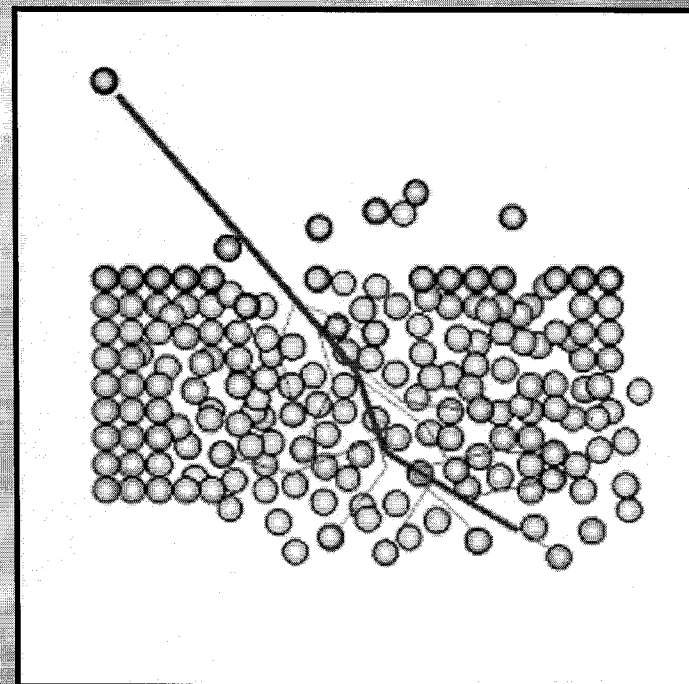


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Physics of SIMS



From the Curie Institute:
<http://www.curie.u-psud.fr/U350/SIMS.html>

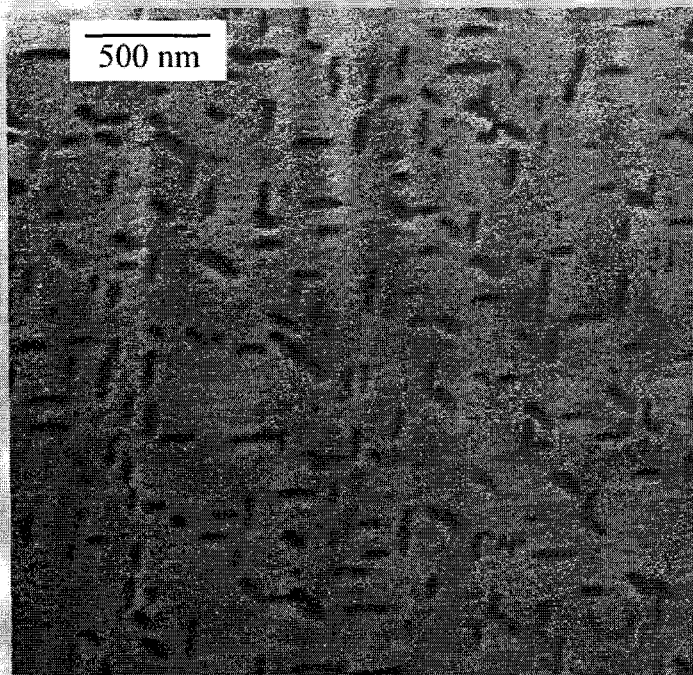


From Cameca:
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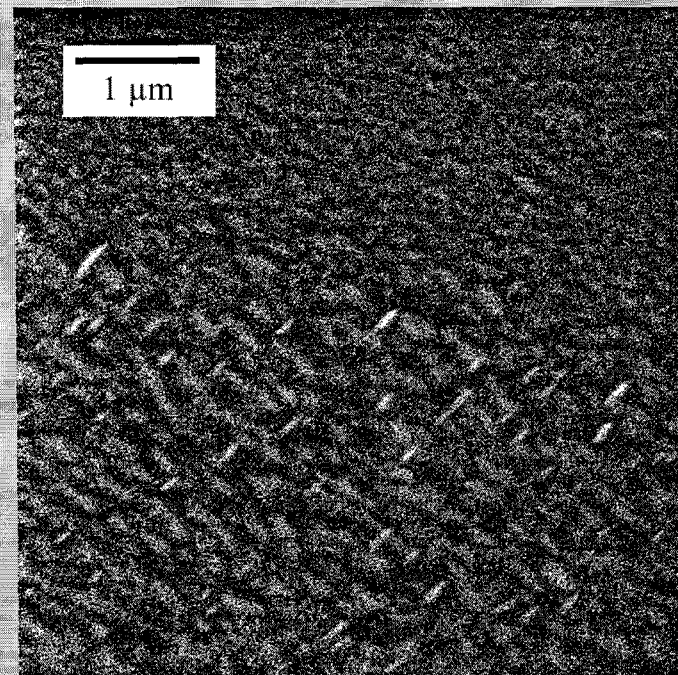


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FIB-SIMS Analysis of Magnetite LP204-1



**Backscattered electron image
of magnetite LP204-1**



**Aluminum image of
magnetite LP204-1.**

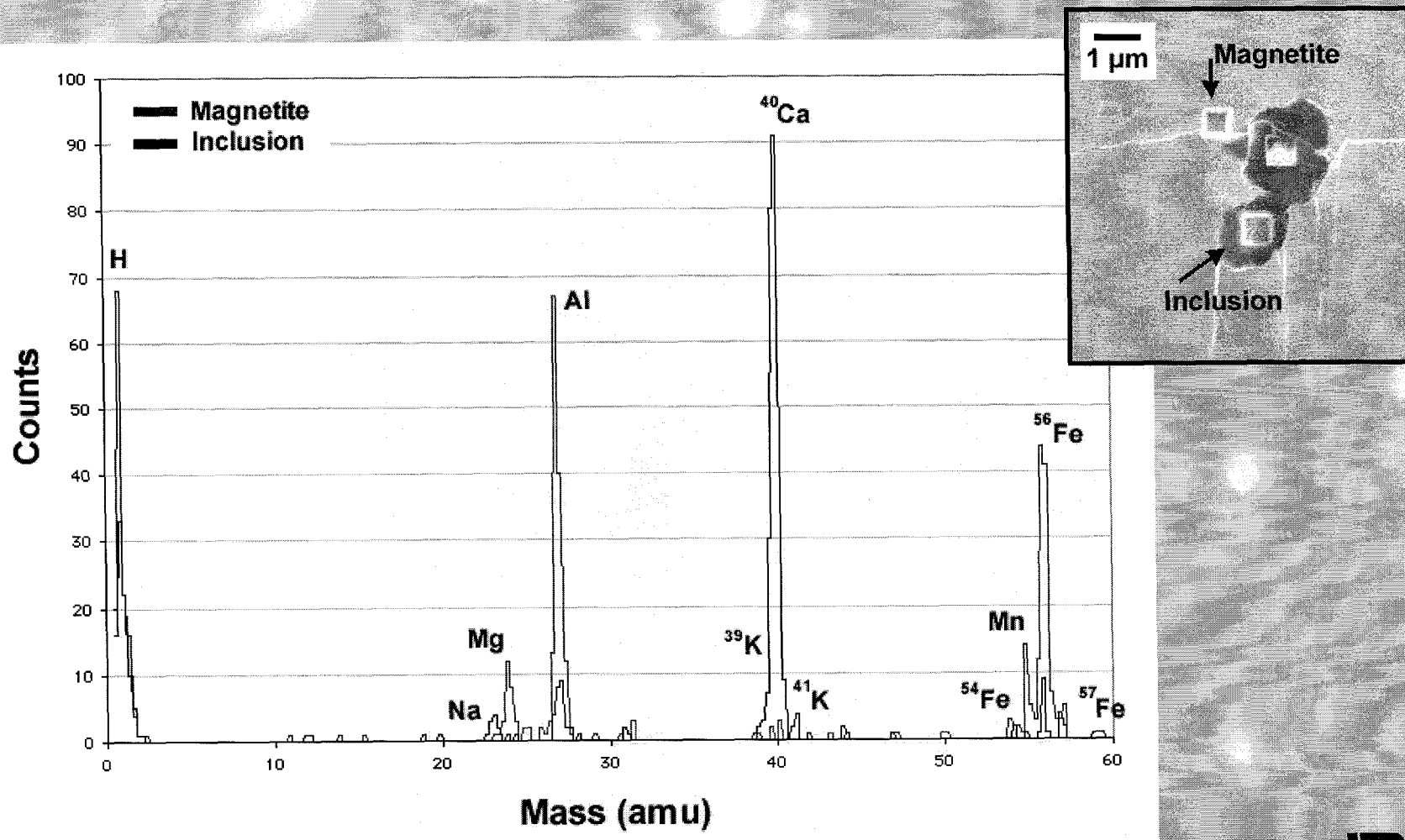


Images taken at the University of Virginia FIB-SIMS Facility.



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FIB-SIMS Mass Spectra from LP204-1 Magnetite

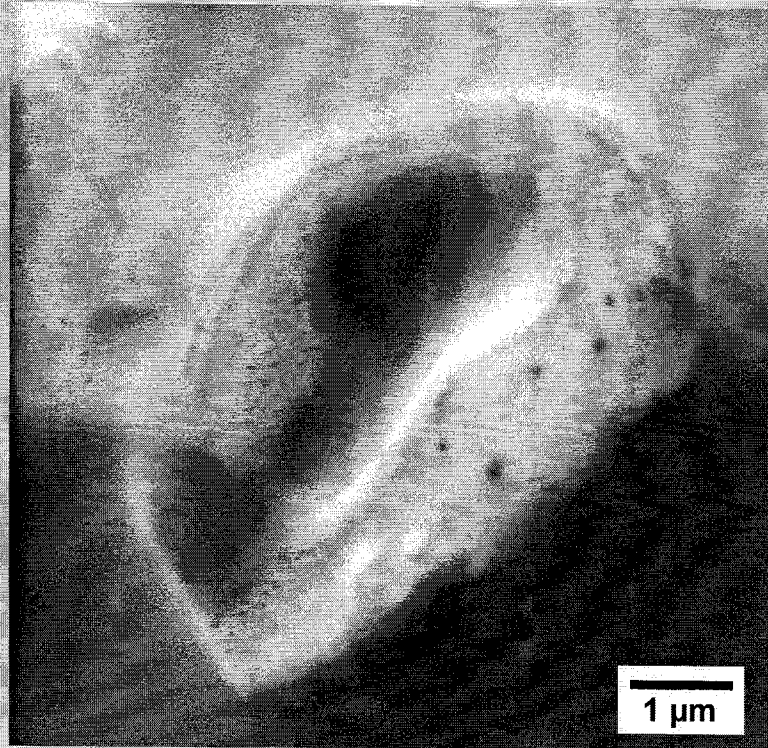


Data taken at the University of Virginia FIB-SIMS Facility.



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FIB-SIMS Cross-Sectioning and Imaging of a Biological Feature



Backscattered electron image of a putative biological feature in an Antarctic microbial community inhabiting sandstone.

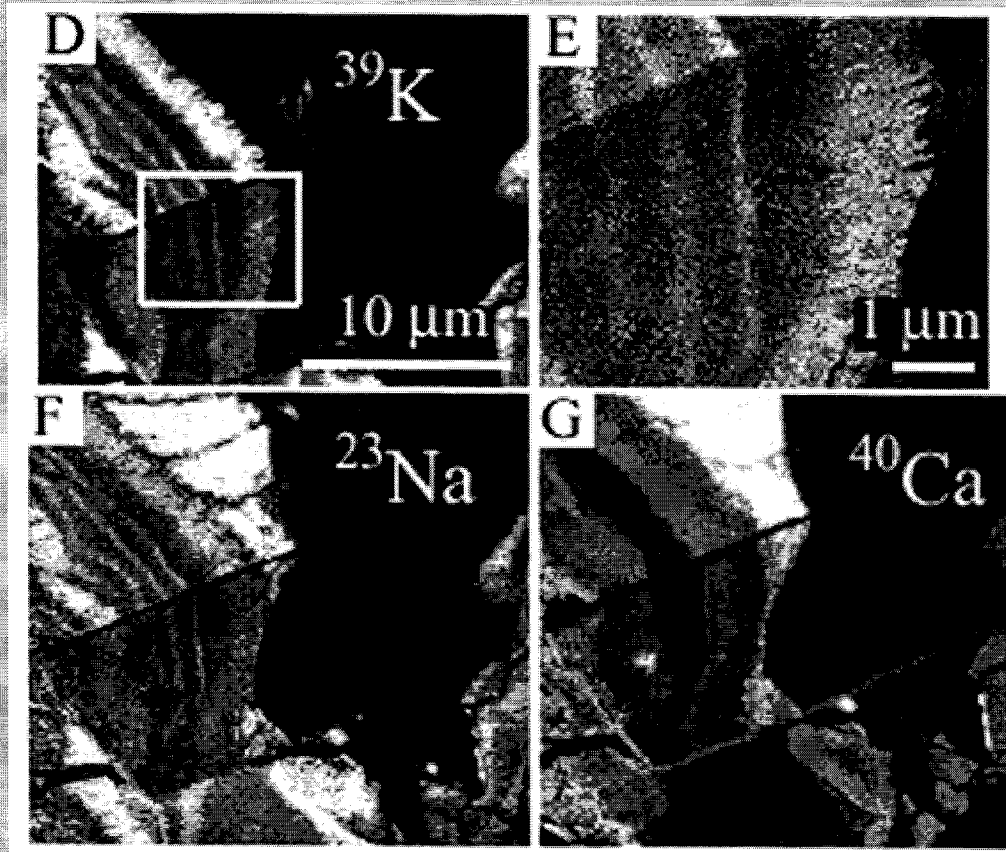


Image taken at the University of Virginia FIB-SIMS Facility.



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Alteration Phases in the Lafayette Meteorite

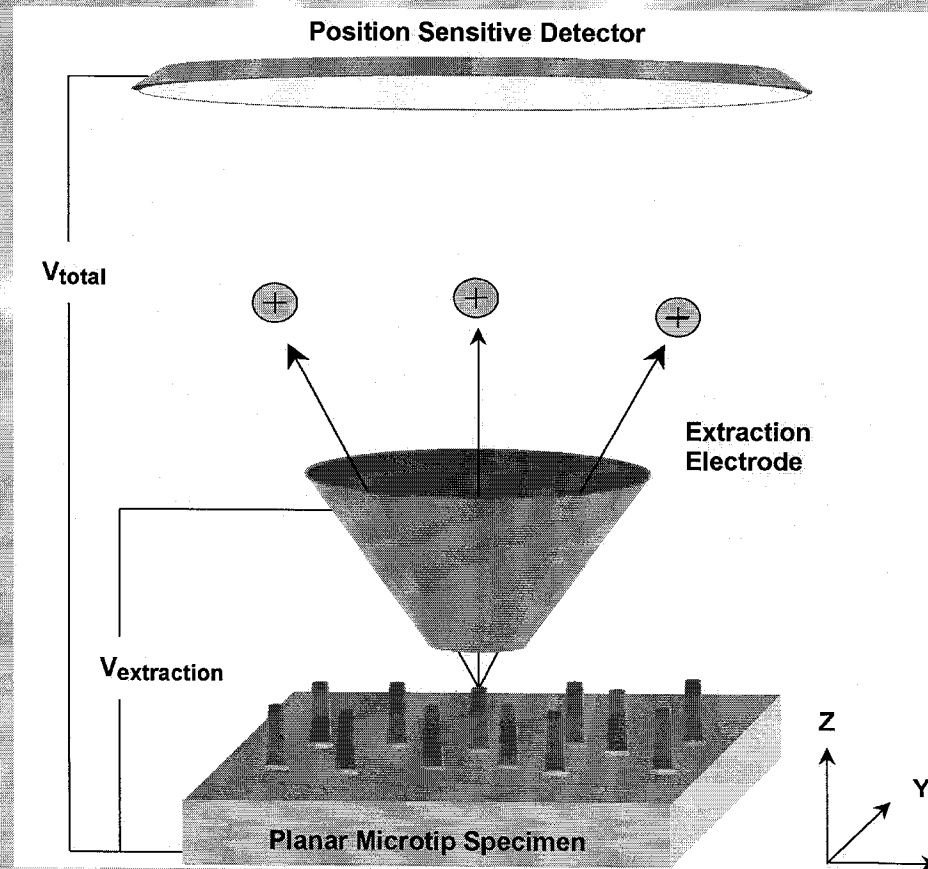


From Vincenzi & Eiler (1998) 61st Annual Meteoritical Society Meeting



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Schematic Illustration of LEAP Microscopy



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Evaporation of Single Atoms



Sequence of FIM images showing evaporation of single atoms of a nickel zirconium intermetallic specimen from the topmost atomic plane.

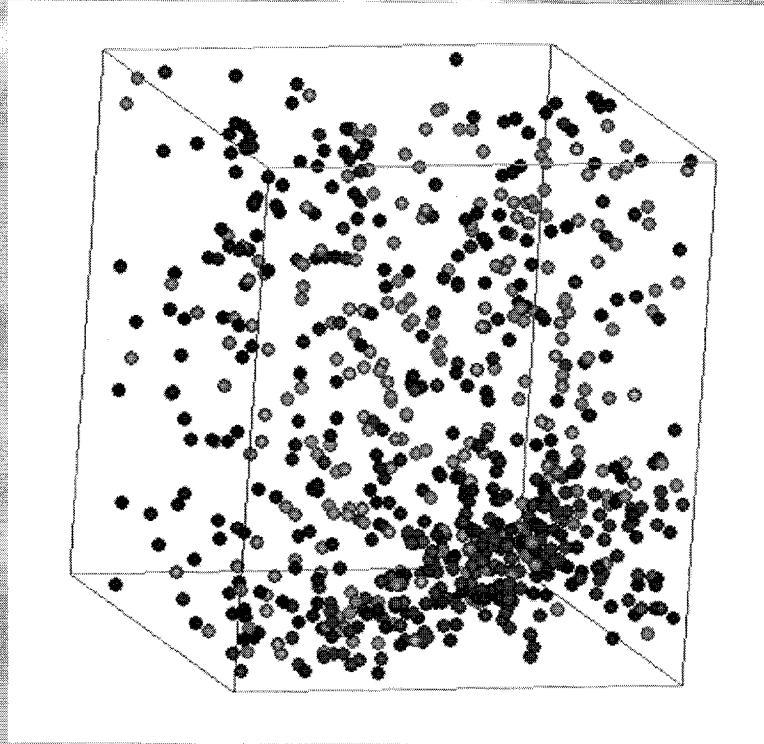


From Miller, et al. (1996) Atom Probe Field Ion Microscopy, Oxford University Press



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Analytical Capability of 3DAP

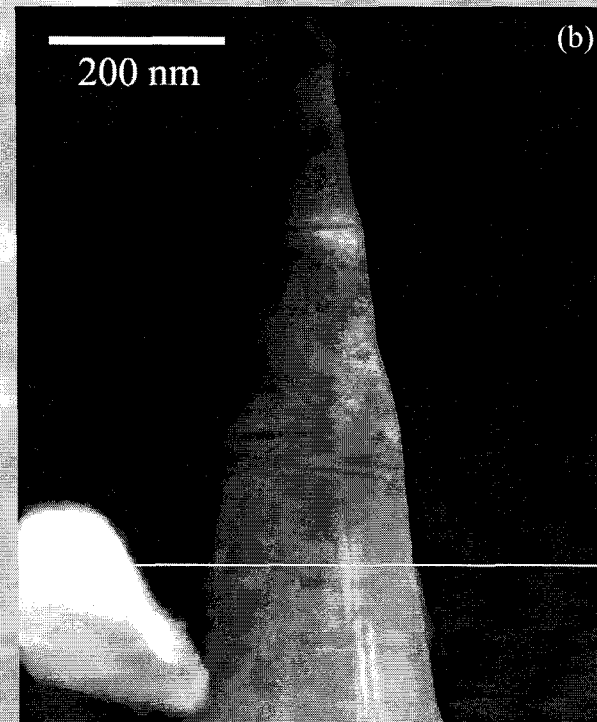
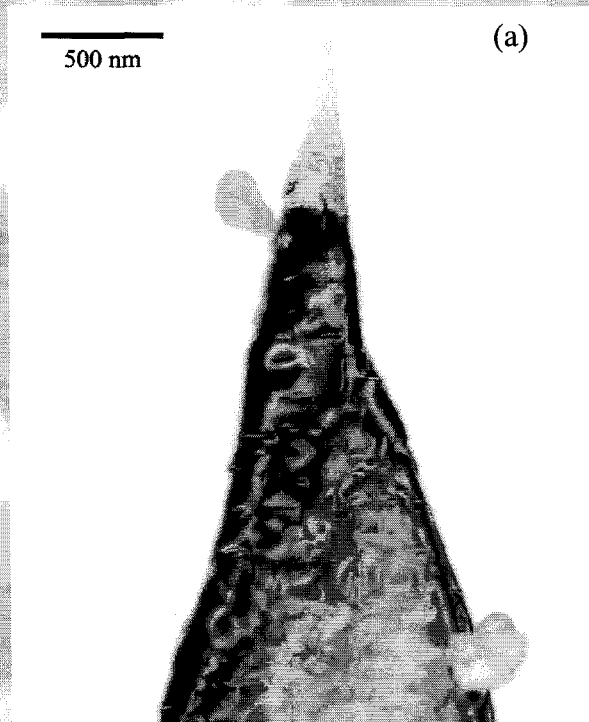


A three-dimensional image of stainless steel showing low levels of boron (red), carbon (green), and phosphorus (blue) at a grain boundary. This analysis was done using the conventional three-dimensional atom probe (3DAP) at Oak Ridge National Laboratory. Other elements (e.g. iron) have been left out of the image for clarity.



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Magnetite Field Emission Tip



Surface after Field
Evaporation

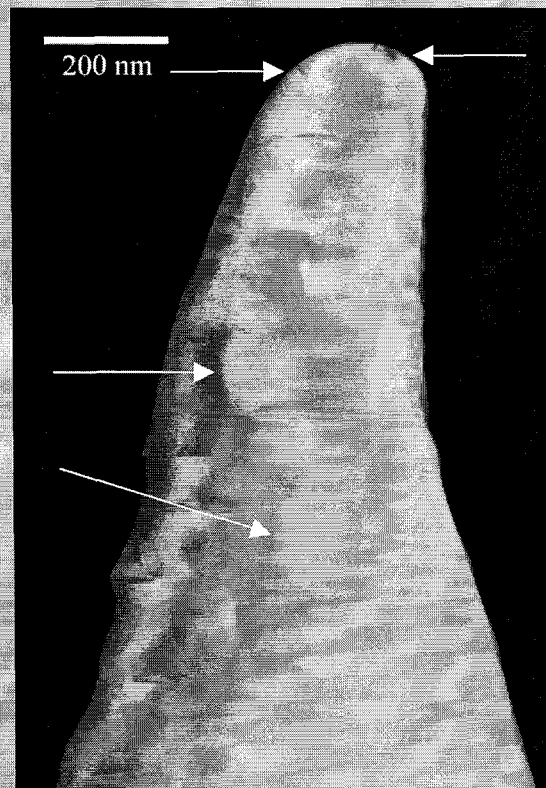
TEM of sample 031300E after resharpener with a Gatan ion mill with 5 keV Ar and gun tilt = 40° . a) Bright field image showing precipitates and bend contour. b) High magnification image of the tip and precipitates seen in FIM images. The line indicates the surface obtained after field evaporation.



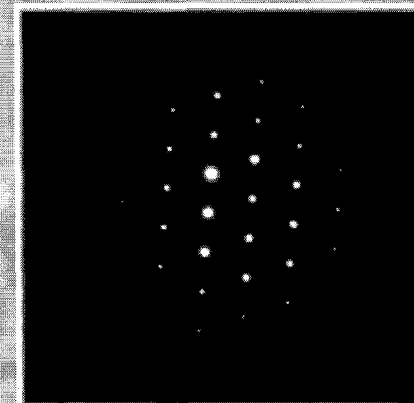
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Post Evaporation TEM Analysis of Magnetite LP204-1

Disk-shaped
precipitates normal
to the beam.



Precipitates seen in FIM
images. The location of
this surface is indicated on
previous slide.



Electron diffraction pattern
indicates that this view is
normal to the [100].



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Field Ion Micrograph of Magnetite LP204-1

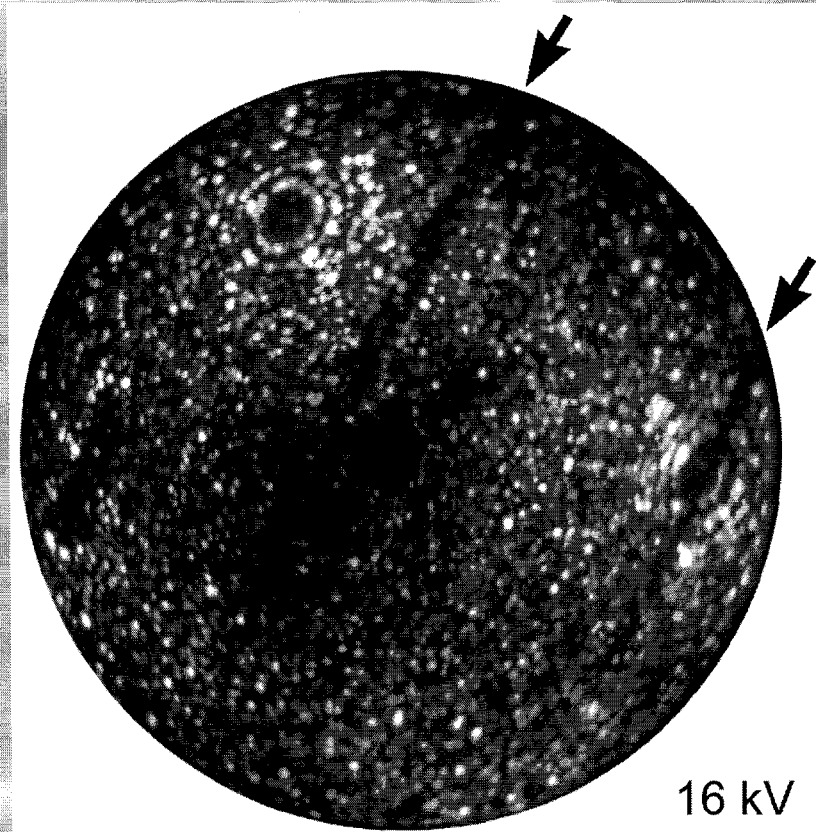
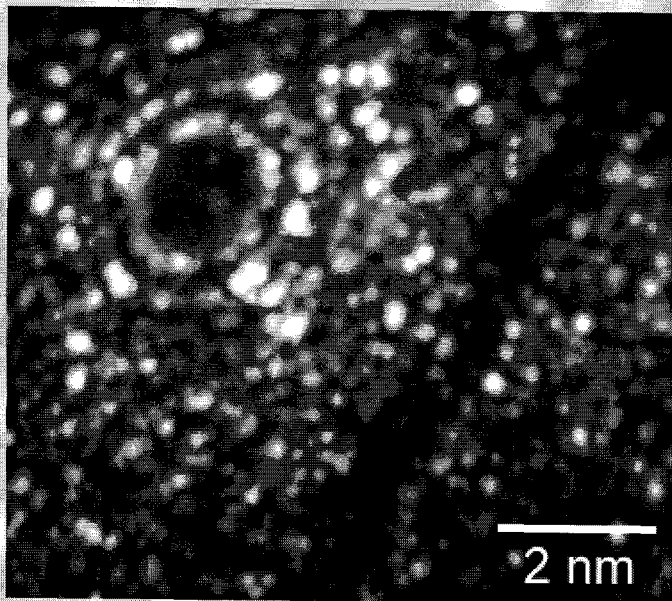


Image is almost normal to the $\{100\}$ axis. Note the clarity of the $\{111\}$ poles and the precipitates running directly through the pole at right of the images.

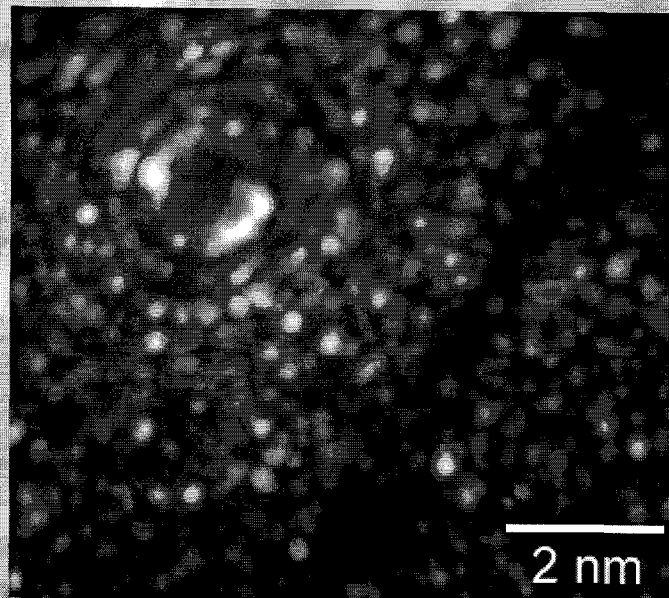


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Six-fold Symmetry of the $\{111\}$ Planes



16.0 kV

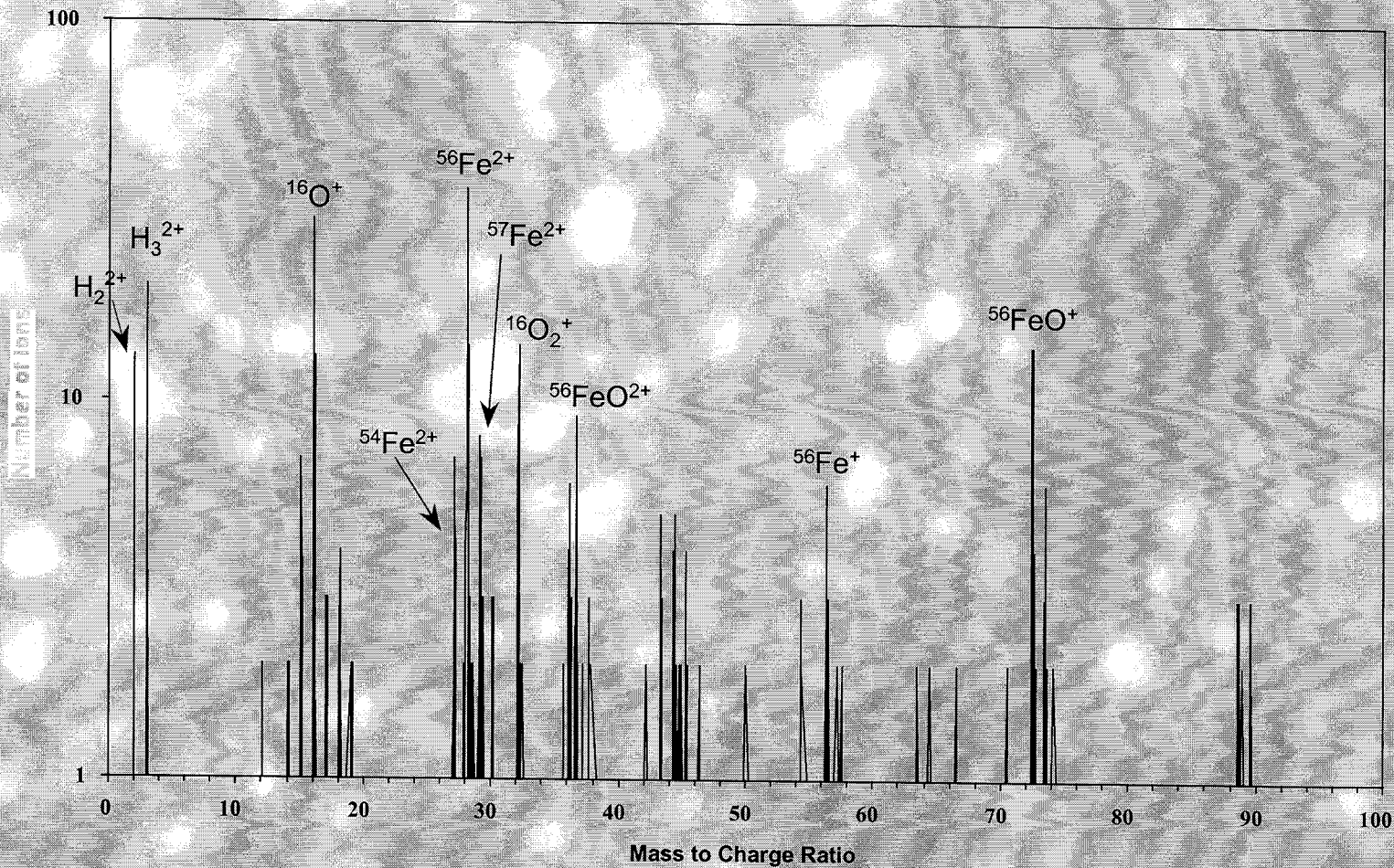


16.5 kV



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First Mass Spectra from a Geological Material using Atom Probe



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Summary

➤ FIB-SIMS Analysis of Magnetite:

- ✧ Allows the in situ fabrication of flat surfaces and the potential for 3-D compositional analysis.
- ✧ Backscattered electron imaging due to sputtering contrast allows imaging of very small lamellae.
- ✧ Elemental imaging is possible with spatial resolution to ~50 nm, but mass resolution and sensitivity needs improvement.

➤ APFIM Analysis of Magnetite:

- ✧ Mass spectra have been obtained showing isotopes of Fe and O as well as FeO.
- ✧ Singly and doubly charged ions are observed.
- ✧ A preliminary mass spectrum taken from a precipitate contains both Mn and Al, as expected from previous analysis of magnetite LP204-1 by Sitzman, et al.



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